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Cost Estimate for Laser Isotope Separation for RIA

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Introduction

Isotope enrichment of some elements is required in support of the Rare Isotope Accelerator (RIA) in order to obtain the beam intensities, source efficiencies and/or source lifetime required by RIA. The economics of using Atomic Vapor Laser Isotope Separation (AVLIS) technology as well as ElectroMagnetic (EM) separation technology has been evaluated. It is concluded that such an AVLIS would be about 10 times less expensive than a facility based on electromagnetic separation - $17 M versus $170 M. In addition, the AVLIS facility footprint would be about 10 times smaller, and operations would require about 4 years (including 2 years of startup) versus about 11 years for an EM facility.

AVLIS

The full list of required elements for the RIA driver beams is [1]:

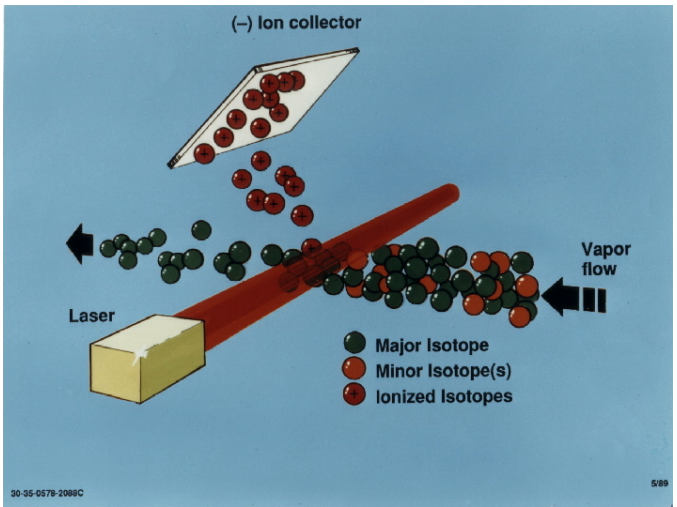
^{18}O, ^{40}Ar, ^{48}Ca, ^{64}Ni, ^{70}Zn, ^{76}Ge, ^{82}Se, ^{86}Kr, ^{96}Zr, ^{124}Sn, ^{112}Sn, ^{136}Xe, ^{176}Yb, ^{192}Os, ^{198}Pt, ^{204}Hg, ^{208}Pb, ^{232}Th, and ^{238}U

Of these, ^{40}Ar, ^{232}Th, and ^{238}U require no enriching, because their natural abundance is greater then 99% in each case. Furthermore, ^{18}O is readily available commercially for about $100/g. The major source of enriched ^{18}O is through the cryogenic distillation of H_2O, NO and, to a lesser extent, CO. Also, enriched ^{86}Kr and ^{136}Xe are available commercially, enriched using centrifuges and/or thermal diffusion. ^{86}Kr costs about $1400/liter (99%), and ^{136}Xe is about $30,000/liter.

Of the remaining list, the elements, Se and Hg, do not lend themselves to the AVLIS technique. These isotopes are presently separated using Calutrons. ^{82}Se costs about $8,260/g and ^{204}Hg is about $192,500/g.

As a result, the isotopes that were evaluated for separation using AVLIS are:

^{48}Ca, ^{64}Ni, ^{70}Zn, ^{76}Ge, ^{96}Zr, ^{124}Sn, ^{112}Sn, ^{176}Yb, ^{192}Os, ^{198}Pt, and ^{208}Pb.



The basic concept of AVLIS is shown in the figure below. A well collimated vapor stream is made, which is then bisected by several laser beams that are precisely tuned to effect resonant stepwise photoionization of the desired

isotope, typically the minor species. The absorption frequencies of the various isotopes are sufficiently separated (typically hundreds of MHz to several GHz) that there is near perfect selectivity. The resulting photoplasma is electrostatically extracted and collected separately from the remainder of the vapor stream that is then condensed out on a collector. Thus, the input vapor stream, a mixture of isotopes is separated into two streams, one enriched in the desired isotope, the other depleted.

The overall system performance of an AVLIS process is characterized by three parameters, the "non selective pickup", φ, which is the fraction of the feed material that ends up in the product; the "stripping efficiency", η, which is the fraction of the desired isotope of interest in the remaining feed material that ends up in the product (photoionized by the laser system); and the "throughput", *F*, or the rate the feed material is processed and separated into product material and by-product material.

The "throughput" is determined by the amount of product required and the efficiency of the enrichment process. That is, given the enrichment factors, the amount of feed material that is processed can be adjusted to achieve the amount of required product material at the required assay. The value of the required "stripping efficiency" is determined by the laser system parameters – laser power, beam quality, and modulation format, for example. These, in turn, are determined by the atomic absorption cross sections, hyperfine splittings, isotope shifts, J-values, etc. of the atomic transitions. By appropriate selection of suitable transitions, typical values of the "stripping efficiency" of 60%-65% are achievable without Herculean efforts from the laser system. For all cases considered here, a value of the "stripping efficiency" of 60% has been assumed.

From experience, a typically achievable value of the "non selective pickup" is ~1%. Almost certainly, lower values can be achieved. As low as 0.1% is possible, but a value of 1% has been assumed in all cases (the non selective pickup dilutes the extracted photoplasma with feed material). Also, in all cases it was assumed that a product assay of 99% has been assumed to be required. To the extent that a lower product assay is acceptable, the amount of feed material that must be processed in order to achieve the product material is reduced as the product assay requirement decreases.

The algebraic relationship between the product rate and the feed rate is:

$$P = [\eta + (1-\eta)\varphi X_F]F,$$

where *P* is the product rate, *F* is the feed rate (also called the "throughput"), X_F is the Feed Assay, φ is the "non selective pickup" and η is the "stripping efficiency".

The easily derived expression for the product assay is:

$$X_P = \frac{[\varphi + (1-\varphi)\eta]X_F}{\varphi + (1-\varphi)\eta X_F}.$$

Note, in the limit of φ=0 that X_P=1 (for any finite value of η) and also in the limit of η=0 then X_P=X_F. In most cases, more than one stage is required to achieve a product assay of 99%. That is, after processing the feed material, the product material with an assay greater than feed, but not yet 99%, is run through the separator again to further enrich it. The product assay requirement is driven by the ECR ion source efficiency, lifetime, and beam intensity requirements.

AVLIS tends to be the least expensive enrichment technology for those missions where a substantial throughput is required and where the mission duration is sufficiently long that the usually substantial up-front investment in hardware and development of the element-specific spectroscopy may be amortized over many years and offset. The differential operating costs of AVLIS tend to be low since it is not a labor-intensive technology. As a result, the usual AVLIS economical model that shows a hardware build-up (and associated expenditures) followed by sustained operations is not as appropriate for RIA where a number of separate missions are strung together in a bunch of relatively short duration campaigns.

The RIA mission requires a generic capability where there is an emphasis on enriching a specific element for a relatively short amount of time, followed by a switch to the next element. In order to address all the isotopes in the above list the generic capability would include three tunable, diffraction-limited dye lasers with a capability of several hundreds of watts average output power, and with frequency doubling capability. Similarly, two tunable diffraction limited 100 W Ti:sapphire lasers also with frequency doubling capability are needed, as well as a special purpose near diffraction limited ArF (for Ge) and a Nd:YAG (for Pt) laser system. The time required to enrich is small in most cases compared to the development and set up time. The atomic spectroscopy, including measured Rydberg level structure (where appropriate), isotope shifts and hyperfine structure will need to be measured in many of the cases but are sometimes available in the literature for other cases.

This information is summarized in Table 1 below. The natural abundance is listed in the in the fourth column, followed by the Ionization Potential. Next is the peak product rate in grams per hour followed by the number of stages required to get to 99% material. From known spectroscopic tables, likely photoionization pathways have been selected. The wavelengths of each transition are listed. Most of the elements require three resonant steps, the last to an autoionizing level. For those elements that require only two resonant steps, or for which there is no accessible autoionizing level, the final level is a Rydberg

level that would subsequently be field ionized. The next column lists the type of laser system, usually Dye or Ti:sapphire. For some of the transitions, Second Harmonic Generation (SHG) of the dye or Ti:sapphire output is required. Finally, the last two columns have been emphasized because they highlight the amount of enrichment time needed to produce 30 grams of 99% product material for and AVLIS system versus a Calutrons system (discussed briefly below). Note that about 2,500 separator hours would be needed to enrich all of these materials using AVLIS technology, versus about 150,000 hours using Calutrons! More on this comparison later when the economics of the two technologies are compared.

Ion	Z	A	X_F	IP (eV)	P_{max} (g/h)	# Stages	Wavelength (Å)	Laser System	AVLIS Time for 30 Grams	Calutron Time for 30 Grams
Ca	**20**	48	0.0019	6.11	0.0230	3	3776 4650	Ti:sap, SHG Ti:sap, SHG	1304	80214
Ni	**28**	64	0.0093	7.63	0.1102	2-3	3146 3356	Dye, SHG Dye, SHG	272	16199
Zn	**30**	70	0.0062	9.39	0.0725	2-3	3077 4723 4526	Dye, SHG Ti:sap SHG Ti:sap SHG	414	24194
Ge	**32**	76	0.0783	7.88	0.9475	2	1934 8407	ArF Ti:sap	32	1916
Zr	**40**	96	0.0280	6.84	0.3396	2	5608 5534 5681	Dye Dye Dye	88	5357
Sn	**50**	124	0.0579	7.34	0.7021	2	2864 8274 7662	Dye, SHG Ti:sap Ti:sap	43	2591
Sn	**50**	112	0.0097	7.34	0.1176	2-3	2864 8274 7662	Dye, SHG Ti:sap Ti:sap	255	15464
Yb	**70**	176	0.1276	6.20	1.5411	2	5558 4233 7471	Dye Ti:sap, SHG Ti:sap	19	1176
Os	**76**	192	0.4093	8.50	4.9658	1	3303 4158 5998	Dye, SHG Ti:sap, SHG Dye	6	366
Pt	**78**	198	0.0716	9.00	0.8733	2	2660 4513 7018	Nd:YAG, SHG Ti:sap, SHG Dye	34	2094
Pb	**82**	208	0.5240	7.42	6.3927	1	2834 6061 7100	Dye, SHG Dye Dye	5	286
Total Separator Hours									2,472	149,857

Table 1: Enrichment information for RIA Drive Beam Isotopes

For an AVLIS system, the separator technology (i.e. the vacuum systems, thermal controls, evaporation system, product and by-product collectors, anode, power supplies, electronics, data collection) is largely generic for all materials: It would involve an off-the-shelf electron-gun vapor source, a collimator with a supersonic expansion slit, high-voltage extractors to extract out the laser-created photoions, and collectors of the remaining vapor stream. There will certainly be material issues that need to be understood when converting from one element to another, but the main separator components will not change much, although the geometry will vary. The controls and labor associated with running the vacuum system will not vary significantly.

Based on years of experience developing the sort of systems required here, it is estimated that this effort would require ~$17 M, and ~4 years with the funding profile of $5.3 M in years 1 and 2, and then $3.3 M in years 3 and 4. The first two years would involve the development of the vacuum/separator system and controls, as well as the laser system required for the first element. In addition, the rest of the generic laser system would be built during the first two years. A rough cost estimate is provided in the Table 2 below.

AVLIS				
Capital Equipment	Number	Unit Cost	Cost	
Separator System	1	1.5	1.5	
Ti:sapphire Lasers (2)	2	0.5	1	
Dye Laser Systems (3)	3	0.5	1.5	
ArF Laser	1	0.1	0.1	
Subtotal			**4.1**	
Labor	Number	Annual Cost		
Scientists/Engineers	4	0.3	1.2	
Technicians (one shift)	6	0.25	1.5	
Subtotal			**2.7**	
		Annual Cost		
Parts and Supplies				
Capital Multiplier	0.2	**0.82**		
Space				
Facility Size (sq ft)	2000			
Cost (burdened)	70			
Total Facility Cost	**0.14**			
Project Costs	Year 1	Year 2	Year 3	Year 4
Yearly Costs	5.3	5.3	3.25	3.25
Cumulative	5.3	10.6	13.85	17.1

Table 2: Cost for a 4-year program to provide isotopes for RIA. Costs are in million of dollars.

Enrichment begins in year 3 and finishes in year 4. At the end of the 4th year, 30 grams at 99% product assay of each of the 11 elements will have been separated.
Note from Table 1 that about 2,500 enrichment hours are needed to enrich 30 grams of product to 99% for all the elements considered. The schedule allows two full years to

complete all the campaigns - roughly one year of cumulative enrichment time and one year of cumulative setup time.

Electromagnetic Separation

The $17 M, 4-year effort for AVLIS in support of RIA drive beam isotopes should be contrasted with the cost associated with Calutrons. The throughput per Calutron is about 300 times lower than an AVLIS separator (depending on which element). This is also shown in the last two columns of Table 1. Because the throughput is so much less for Calutrons, a different concept of operations is required. In order to make up the factor of 300, 10 separators are assumed, running 7,500 hours each year (i.e. 24/7 with periodic maintenance), running for 10 years. It is assumed that, since so much enrichment time is required for each element, running three shifts per day, that there would be sufficient time and staff to prepare for the next element while enriching the present element. Both this assumption and the 7,500 enrichment hours/year may be moderately aggressive assumptions.

Operating costs have been estimated in an ORNL white paper "Calutron Enrichment of Plutonium Isotopes", Dec. 1998 [2] to be $4.3M/y plus an additional $2M/y for each additional separator, if required. These costs assume 24/7 operations, 50 weeks a year. In addition, if ORNL were to do the separation, substantial restart costs would be incurred (~$10M). Certainly the ORNL costs are impacted by the ES&H rigors imposed by plutonium, but the Oak Ridge stable isotope separation facility is part of the facility that was used to separate the actinides.

As another approach using the same technology, there is a Belgium company, IBA, which is now selling an Electro-Magnetic Isotope Separator, EMIS 250, based on Calutron technology. As of May 2003, however, no system had yet been built. Their claim is that the throughput is about 2 times that for Oak Ridge (experienced and knowledgeable ORNL personnel believe this is optimistic).

The capital cost per separator is $3.5 M with an additional $1.5 M required for installation. To run 24/7 with 10 separators would require $10.7 M/year. A rough estimate of electromagnetic separation is given in the table below. During the first year, installation and initial operations would be conducted. Enrichment operations would begin in year two, and run for the next 10 years, requiring about $10.7 M/y (just the first 3 years of operations are shown). Thus, the total project cost would be about $168 M over eleven years.

Electromagnetic Separation				
Capital Equipment				
EMIS 250	10	3.5	35	
Installation	10	1.5	15	
Subtotal			50	
		Annual		
Labor	Number	Cost		
Scientists/Engineers	4	0.3	1.2	
Technicians (three shifts)	10	0.25	2.5	
Subtotal			**3.7**	
		Annual		
		Cost		
Parts and Supplies				
Capital Multiplier	0.1	**5**		
		Annual		
Space		Cost		
Facility Size (sq ft)	20000			
Cost (burdened)	100			
Total Facility Cost	**2**			
Project Costs	Year 1	Year 2	Year 3	Year 4
Yearly Costs	60.7	10.7	10.7	10.7
Cumulative	60.7	71.4	82.1	92.8

Table 3: Cost of a 4-year Calutron program for RIA isotopes. Costs are in million of dollars.

Thus, AVLIS project costs are estimated to be $17 M over 4 years versus $168 M over 11 years.

Summary
Isotope enrichment of certain elements is required in support of the Rare Isotope Accelerator in order to obtain the beam intensities, source efficiencies and/or source lifetime required by RIA. A multi-element facility based on AVLIS technology has been evaluated both technically and economically. It is concluded that such a facility would be about 10 times less expensive than a facility based on electromagnetic separation ($17 M versus $170 M). In addition, the AVLIS facility footprint would be about 10 times smaller, and operations would require about 4 years (including 2 years of startup) versus about 11 years for Calutrons.

References:
[1] R.C. Pardo, C.L. Jiang, J.N. Nolen, K.E. Rehm and G. Savard, Proceedings of the 10th International Conference on ION SOURCES, Dubna, Russia, September 8-13, 2003, Rev. Sci. Instrum. 75, 1427 (2004). See also, Richard Pardo, "Heavy-Ion Beams Required for the RIA Accelerator", RIA Facility Workshop, East Lansing, Michigan, March 9-13 2004, and Claude Lyneis, "Update Driver Linac Working Group Ion Production and Interface Issues", RIA Facility Workshop, East Lansing, Michigan, March 9-13 2004, at http://meetings.nscl.msu.edu/ria2004.

[2] White paper by Emory D. Collins, Joe G. Tracy and W. Scott Aaron, "Calutron Enrichment of Plutonium Isotopes", ORNL, Dec. 1998.